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No. 281

COMBUSTION OF LIQUID FUELS IN DIESEL ENGINE.

By Otto Alt.

From "Zeitschrift des Vereines deutscher Ingenieure,"
July 14, 1923.

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS.

TECHNICAL MEMORANDUM NO. 281.

COMBUSTION OF LIQUID FUELS IN DIESEL ENGINE.*

By Otto Alt.

In order to employ liquid fuels for generating power, either the engines must be adapted to the fuels or the fuels to the engines. Many attempts are now being made in both these directions. While thus far the endeavors of engine designers have been almost entirely in the former direction, the oil industry has recently begun to experiment in the latter direction.

Hitherto, definite specifications have always been made for fuel oils and they have been classified as more or less good or non-utilizable. The present aim, however, is to build Diesel engines capable of using even the poorest liquid fuels and especially the waste products of the oil industry, without special chemical or physical preparation. Herein lies the great economy of the Diesel engine.

Of the chemical characteristics of liquid fuels, the following are important, as affecting the use of these fuels in Diesel engines:

1. General chemical composition, for judging:

- a) The nature of the ignition and combustion and the requisite devices therefor;
- b) The effect of any sulphur compounds on the engine parts which come in contact with the fuels themselves or with their combustion products;

* From "Zeitschrift des Vereines deutscher Ingenieure," July 14, 1923, pp. 686-691.

c) The effect of any asphalt residues, especially as a result of incomplete combustion;

d) The effect of any free carbon.

2. Ash content, consisting of incombustible inorganic compounds or residues of the salts of organic acids which, after combustion, adhere to the engine parts and may cause excessive wear.

3. Heating value, for the approximate appraisal of the nature of the fuel and for the determination of the heat consumption and thermal efficiency.

The following physical characteristics of liquid fuels are important:

4. Specific gravity, for the approximate appraisal of the nature and heating value of the fuel and for the determination of the amount of space required for storing it.

5. Flash and combustion points, for determining the nature of the fuel and the fire danger and the requirements in regard to storing.*

6. Boiling-point curve, for the determination of the qualitative and quantitative composition from the boiling points of the constituents, as obtained by fractional distillation.

7. Viscosity at different temperatures, for determining the degree of fluidity and the means for conducting the fuel to the engine and the spraying into the combustion chamber by means of air or mechanical pressure.

Here belong also, for the technical treatment of the fuels, the
* Paragraphs 4 and 5 have nothing to do with the functioning of the engines.

water content and mechanical impurities, which can be reduced by abstraction, evaporation and filtration, so as to meet the requirements for continuous functioning.

On account of the tremendous importance of coal and petroleum, the chief natural sources of liquid fuels, scientists are endeavoring to solve all the details of their treatment.

The Diesel engine employs fuels obtained from the petroleums of different countries and also from lignite and coal tars. Sometimes the raw materials (crude petroleum, lignite tar and coal tar) are used as fuels. Vegetable oils can also be used.

The hydrocarbons in liquid fuels comprise two classes: the aliphatic or chain class and the cyclic or ring class. The former class includes the paraffins ($C_n H_{2n+2}$) and the olefins ($C_n H_{2n}$), while the latter class includes the aromatic hydrocarbons and the hydro-aromatic hydrocarbons or naphthenes. In general, the fuel oils are very complex mixtures of hydrocarbons of both classes and are termed either aliphatic or aromatic fuels, according to the predominance of one or the other class. The difference in the molecular structure of the two classes gives the fuels very different properties and materially affects their combustion in the Diesel engine.

In order, therefore, to characterize a fuel oil, it is only necessary to establish its content in aliphatic and aromatic compounds and naphthenes. The aliphatic fuel-oils are the ones obtained from petroleum (including gas oils and residues), lignite

tar (paraffin oils), shale oils and vegetable oils. The aromatic oils are the ones obtained from coal tar. Natural tar oils are generally mixtures of both classes. According to recent analyses* the aromatic compounds seem to predominate in these oils.

The following purely chemical consideration is fundamental for estimating the ignition and combustion temperatures of fuel oils in the Diesel engine. The conversion of energy in the engine is effected by oxidation at a high temperature and pressure. Possibly freed hydrogen also plays a role. If the effect of pressure (which, in the Diesel engine, is small in comparison with the effect of the temperature) be disregarded, the fuel oils are subjected to three actions in the engine: 1) Thermal decomposition; 2) Oxidation; 3) Hydrogenation.

Privy Councillor Fischer and his coworkers have initiated, in this connection, decisive investigations at the "Kohlenforschungsinstitut" (Institute for the study of coal) in Mülheim on the Ruhr**. The object of the researches on the oxidation of fuels under pressure is to acquire a scientific insight into the different stages of the combustion and to obtain intermediate products of higher value than the final results of the combustion. The hydrogenation experiments were undertaken in order to convert the large amount of phenol occurring in natural tar into benzene (known commercially

* Weissgerber and Moehrle, "Beiträge zur Kenntnis der Urteeröls," Brennstoff-Chemie, Vol. IV (1923), p. 81.

** Gesammelte Abhandlungen zur Kenntnis Kohle," Vols. I-V, (1917-1921).

by the name of "benzol") and to explain the formation of the aromatic tar. By comparing the results of these experiments regarding the three kinds of action on the hydrocarbons in the fuel oils, we come to the following conclusions:

1. The fuel oils exhibit a similar behavior toward the three kinds of action;

2. The different compounds, however, behave very differently. While the paraffins, olefins and naphthenes are easily split, the aromatic compounds strongly resist decomposition;

3. In the case of aromatic compounds, the splitting, even by hydrogenation, yields other aromatic compounds, in contrast with paraffins and olefins (which yield gases almost exclusively), with only traces of aromatic compounds.

4. The oxidizability increases in the order: benzene, naphthalene, anthracene. Benzene offers the greatest resistance to oxidation of any of the liquid hydrocarbons.

5. In either oxidation or hydrogenation, the stability increases in the order: cymene, xylene, toluene, benzene.

6. In general, the more complex the molecule, the easier it can be decomposed.

Sulfur compounds, which occur in nearly all fuel oils (about 1% in coal-tar oils, 2% in lignite-tar oils and as high as 5% in Mexican petroleum), are present in aliphatic fuel oils partly as chain and partly as ring compounds and in aromatic oils as ring compounds. They can be removed from petroleum distillates by means

of copper oxide, according to the Frasch process, and from tar oils by means of copper and zinc. These methods are not practicable for Diesel engine fuels, on account of their high cost. Diesel engine designers must therefore reckon with sulfur compounds both before and after combustion. It has been found that the combustion products of sulfur (sulfur dioxide, SO_2 , and sulfuric anhydride, SO_3) can not combine with the water vapor to form sulfurous and sulfuric acids, on account of the high temperature (Graefe, "Der Olmotor," Vol. I, 1912, p. 89). These acids are probably formed, however, by the condensation of the water vapor in the exhaust pipes. If, from lack of tightness of the cooling chambers, water enters a cylinder along with the combustion air, it may cause the formation of acids and consequent corrosion of the cylinder and piston. This may easily happen. Hence special provision should be made for the rapid removal of the water, when fuels containing sulfur are employed.

There seem to be differences in the corrosion of metals by the sulfur compounds, due to the fact that the ring compounds attack copper and its alloys and wrought iron, while having practically no effect on cast iron and nickel steels (Weissburger, Brennstoff-Chemie, Vol. II, 1921, p.1). By employing the Frasch method on Mexican oil distillates, Sissingh recently effected only a slight removal of the sulfur, as compared with the results obtained by the application of the same process to Canadian and Ohio crude oils, from which he concludes that the sulfur compounds in

the latter oils have a greater affinity for metal oxides (Brennstoff-Chemie, Vol. IV, 1923, p. 113). It is also possible that the danger of corrosion from Mexican oils, notwithstanding their high sulfur content, is less than from coal-tar oils. Further investigation of the whole problem is necessary.

Some crude petroleums and their residues, especially the Mexican, contain large quantities of asphalts (up to 20%). Some of these asphalts are hard, with a high melting point, and are precipitated by gasoline, while others are soft, melting under 100°C (212°F), and are precipitated by ethyl ether. They are all oxygen and sulfur-containing hydrocarbons of high carbon content. Their smokeless combustion, as Graefe has already shown (Brennstoff-Chemie, Vol. IV, 1923, p. 113), generally presents no difficulty, since the complex asphalt molecules are easily decomposed.* It is still to be determined as to whether the coke-like deposit, formed by such fuels in the engine cylinders, is due to the asphalt or ash content or to both.

The asphalts occurring in coal tar and coal-tar oils behave differently. They may also be rich aromatic compounds, which are not entirely consumed in the short time available in the engine. Hard carbon particles are formed, which are deposited in the cylinder in the form of a crust and, in four-stroke engines, are hammered on the seats of the exhaust valves, rapidly closing them up.

Free carbon occurs only in coal tar, where it varies according

* The contrary view, recently expressed by Harold Moore in "The Engineer," Vol. 135, 1923, p. 127, is difficult to understand.

to the variety of the tar. According to the experiments by Constant and Schlapfer ("Über Treiböle," Zeitschrift des V.D.I., Vol. 57, 1913, p. 1489), this component is not pure carbon, but contains about 2.5% hydrogen and 4 to 5% oxygen and nitrogen. On account of its high carbon content, it is consumable with difficulty in the engine and is found again in the exhaust gases in the form of hard carbon particles with the same effects as in the case of the aromatic asphalts.

The ash content, as remarked by Graefe, is not necessarily connected with the physical impurities, since it may be found in oils which have passed through the finest filters. In order to get the correct result, we must therefore determine the ash content of the filtered oil, just as it is burned in the engine. Unfortunately, in the literature, there are to be found ^{too} few and unsatisfactory chemical analyses of the ash constituents for determining whether the greater incrustation in engines operated with residues is due to residual ash components or to carbon deposits or to both. It may be assumed that such effects can be partially prevented by a better lubrication of the pistons and cylinders and by making the inner surfaces of the cylinders harder.

The kind of fuel can be approximately determined by the heating value, specific gravity, flashing point and combustion point. A good graphic representation of the heating value and specific gravity of the fuel oils has been given for this purpose by Schenker ("Brennstoffe und Schmieröle für Dieselmotoren," Winter-

thur, 1919). Fig. 1 shows how the boiling curves can be used for determining the qualitative and quantitative composition of fuel oils. Here the boiling curves of both tar-oil components (naphthalene oil and anthracene oil) are plotted and also the boiling curves of two tar oils. The Haltermann tar oil conforms to the customary pre-war specifications, ordinarily a mixture of 60% naphthalene oil and 40% anthracene oil. Here is also given the boiling curve of the Lindenhof tar oil supplied after the war. On account of the scarcity of tar oil during the first years after the war, a larger proportion of anthracene oil was allowed, since more of this oil than of naphthalene oil is obtained by distilling tar. A slight impairment of ability to withstand cold had to be tolerated.

For judging the composition of these four fuel oils, I have introduced the boiling points, according to A. Spilker,* of the chemical compounds contained in coal tar. The boiling curve of naphthalene oil lies chiefly in the vicinity of the boiling point of naphthalene, the boiling curve of anthracene in the vicinity of the boiling points of Fluorene ($C_{13}H_{10}$), Phenanthrene ($C_{14}H_{10}$) and anthracene ($C_{14}H_{10}$). The boiling curves of the Haltermann and Lindenhof tar oils occupy an intermediate position, the former lying nearer the boiling curve of naphthalene oil and the latter nearer that of anthracene oil. A similar method may also be employed for fuel oils from petroleum and lignite.

The viscosity of the distilled fuel oils is generally so slight

* "Kokerei und Teerprodukte der Steinkohle," 3. Aufl. (third edition), Halle, 1920.

that they present no difficulties in being conducted, pumped and sprayed. Some crude petroleums, most of the residues and the tars are often so viscous, however, at ordinary temperatures that they can not be used in their original condition. Only at a high temperature does their viscosity approach that of the distilled fuel oils. The copious data published by Constan and Schl pfer on this subject are still valuable. Experiments show that a viscosity of about 10 Engler degrees are requisite for conduction and pumping. Mexican fuel oil, for instance, must be heated to about 80°C (176°F). Whether this degree of fluidity is sufficient for satisfactory spraying and combustion is yet to be determined.

Combustion in the Diesel engine.— Hitherto it has been generally assumed that the combustion process in the Diesel engine comprises four more or less distinct stages:

1. Injection of fuel,
2. Vaporization,
3. Ignition,
4. Combustion.

Researches since my lecture in 1920, however, make this appear doubtful.* It may now be regarded as highly probable that no vaporization, in the sense of thermal decomposition, occurs before the ignition. Nevertheless, I will retain this division of the combustion process, in order to distinguish the separate phases and compare our present with our former views.

* "Der Verbrennungsvorgang in der Dieselmachine," "Zeitschrift des V.D.I., Vol. 64, 1920, p. 637.

Injection.- Diésel sought to effect the finest possible atomization of the fuel and there has since been no abatement in this direction. Concerning the conditions under which the finest vaporization is attainable, how far the division can be carried, what effect it has on the fuel consumption and what relation it bears to the excess of air, there are still no conclusions based on numerical data, although accurate experiments would be of the greatest importance, not only for Diesel engines but also for all internal combustion engines using liquid fuels.

In the field of the internal combustion engine, Heuser has published a short contribution on the smallness of the drops attainable in the carburetor and on the method for measuring them.* He ultimately restricted himself, however, to estimating their size by eye, by observing the carburetor cloud in the intake manifold, and found that the diameter of the particles could hardly be smaller than 0.01 to 0.005 mm (0.0004 to 0.0002 in.). The results of physical investigation show, however, that in the atomization of oil, drops of 0.01316 to 0.00063 mm (0.0005181 to 0.0000248 in.) diameter were obtained. The drops are probably still smaller at the high velocities in the atomizer of a Diesel engine. The measurement of the size of the drops does not appear to me to be so very difficult. Furthermore, I believe the size of the drops can also be computed according to the laws of capillarity and surface tension.

That the fineness of the atomization plays an important role in

* "Untersuchungen des Vorgangs im Spritzvergasser," Autotechnik, 1922, p. 3.

the combustion in a Diesel engine is evident from the following considerations. The finer the atomization, the higher the velocity of the fuel particles in the airstream. The heating and, consequently, the ignition are accelerated by increasing the fineness of the spray and the velocity of the particles. Moreover, the fuel particles are driven into the most distant parts of the combustion chamber. The atomization must be effected in such a manner that the particles can not subsequently unite again. The distance from the injection point to the exit from the nozzle plate must therefore be as short as possible.

Vaporization.-- According to Rieppel's theory, the vaporization plays a special role in the scientific consideration of the combustion process in the Diesel engine. In the varied behavior of fuel oils heated in a "bomb" the criterion for judging their utilizability in the Diesel engine was thought to have been found. Riedler and Löffler adopted this conclusion ("Ölmaschinen," Berlin, 1922). Neumann elaborated the bomb experiments with especial thoroughness and apparently amplified and strengthened the conclusions of Rieppel ("Zeitschrift des V.D.I.," Vol. 62, 1918, p.706).

If it were correct that a fuel oil is better in proportion to the amount of oil gas it forms at a low pressure and temperature and in proportion to the continuity of the formation of this oil gas, then the bomb experiments with the accompanying gas analyses would have to be accepted as a good basis for judging various fuel oils. These considerations led me to suggest certain experiments which

were executed in the chemical laboratory of Friedrich Krupp's steel works at Essen. These experiments assumed a decisive trend when the ignition temperatures of the gaseous constituents of the fuel oils in the bomb (which were of the same chemical composition and concentration as in Neumann's experiments) were determined according to Dixon's method. The following ignition temperatures were obtained.

Table I.

Pure Oil	Ignition points of oil gases in oxygen, according to Dixon.	Ignition points of fuel oils in oxygen stream in V ₂ A crucible.
Paraffin oil	614-655°C (1137-1211°F)	240°C (464°F)
Light oil from natural tar	615-651°C (1139-1204°F)	326°C (610°F)
Tar oil	645°C (1193°F)	445°C (833°F)
Vertical-furnace tar	635-661°C (1175-1222°F)	468°C (874°F)

In contrast with the behavior of fuel oils in the Diesel engine, these temperatures differ but slightly from one another. Since the researches of Holm on ignition temperatures ("Zeitschrift des V.D.I., Vol. 62, 1918, p.706), which Constam and Schläpfer extended to a large number of fuel oils, it has been found that the fuel oils present characteristic differences in their spontaneous-combustion temperatures. These ignition temperatures were therefore repeated in the Essen laboratory and simultaneously executed with the igni-

* Wollers and Ehmcke, "Der Vergassungsvorgang der Treibmittel, die Ölgasbildung und das Verhalten der Öldämpfe und Ölgasse bei der Verbrennung im Dieselmotor," Krupp'sche Monatshefte, Vol. II, 1921, Page 1.

tion-point tester proposed by Moore (The Automobile Engineer, 1920, p. 199). By this method, the four fuels in the third section gave quite different temperatures. While the ignition temperatures of the oil gases derived from the fuel oils thus presented no basis for judging their behavior, the fuel oils themselves behaved the same in the ignition experiments as in the engine. Even differences in the time required for vaporization gave no difference worth mentioning in the composition and hence in the ignition point of the gases.

From these researches and chemical considerations, the conclusion must be drawn that there is no oil-gas formation in the sense of Rieppel, Riedler-Löffler and Neumann. Even before the researches of Woller and Ehmcke, I had come to the same conclusions as regards tar oils, on the basis of the literature on pyrogenetic decomposition, in my lecture of November, 1919, before the "Schiffbautechnische Gesellschaft" (Jahrbuch der Schiffbautechnischen Gesellschaft, Vol. 21, 1920, p.389). The same view was also expressed by Von Wartenberg ("Verbrennungsvorgänge in Dieselmotoren," a lecture before the "Westpreussischer Bezirksverein des V.D.I." on November 8, 1921). The temperature in the combustion chamber is too low and the time much too short for pyrogenetic decomposition.

As regards evaporation, does it precede ignition and what significance does it have? Fig. 2 gives the vaporization curves of a series of fuel oils, including those given in Fig. 1, together with the ignition temperatures, as obtained in the Essen laboratory. Table II gives, in parallel columns, the mean boiling points and

the corresponding ignition temperatures of these oils. According to Dalton's law, the compressed combustion air probably does not affect the evaporation of the oil after its injection into the combustion chamber, at any rate of the first few drops, which are still cold, i.e., the evaporation proceeds according to Fig. 2, and the boiling and ignition temperatures may be compared.

Table II.

Fuel oil	Mean boiling point	Ignition point in oxygen stream in V_2A crucible
Gasoline	75°C (167°F)	285°C (545°F)
Benzene	85°C (185°F)	507°C (945°F)
Gas oil	270°C (518°F)	255°C (491°F)
Mexican fuel oil	300°C (572°F)	276°C (529°F)
Paraffin oil	255°C (491°F)	240°C (464°F)
Light tar oil	214°C (417°F)	326°C (619°F)
Naphthalene oil	227°C (441°F)	475°C (887°F)
Anthracene oil	297°C (567°F)	425°C (797°F)
Haltermann tar oil	250°C (482°F)	471°C (880°F)
Lindenhof tar oil	301°C (574°F)	---
Vertical-furnace tar	260°C (500°F)	463°C (865°F)

If vaporization were important for ignition, then the higher the ignition point above the boiling point, the better it would be. Then the oil drops would be more thoroughly vaporized before their ignition and could be more thoroughly mixed with the combustion air.

The opposite, however, obtains for gas oil, paraffin oil and Mexican fuel oil. Entirely apart from the brief period of time available in the engine, these oils are not completely evaporated when the ignition begins. I believe I am justified, therefore, in claiming that the vaporization is of no special importance for the course of the combustion. Von Wartenburg is of the opinion that the combustion, due to the shortness of the time, proceeds at first only in the vapor envelopes of the drops and that the latter remain intact until completely consumed.

Ignition.-- The uniform characteristic of the ignition-point tests by Holm, Constam and Schl pfer and Moore, is the bringing of the drops of fuel oil into contact with a surface of porcelain, platinum or iron, which is heated to the ignition point by some external source of heat. Wollers and Ehmcke attained a high degree of accuracy by considerably improving Moore's ignition-point tester. The latest Krupp ignition-point tester (Fig. 3) comprises an electric furnace c with ignition block a, of non-corrosive (V_2A) steel, temperature-measuring device, oxygen-delivery pipe b, and electric wire (Krupp'sche Monatshefte, Vol. IV, 1923, p. 69). If, in the determination of the ignition point, the temperature of the ignition block, measured by means of a thermo-electric couple, approaches the ignition temperature of the fuel, the latter is then delivered in drops, accompanied by a constant flow of oxygen, until the ignition is evidenced by a distinct report. The ignition point

is then computed from the temperature of the ignition block at the instant of the explosion and from the temperature in the ignition chamber, measured with the aid of a second thermo-electric couple.

Wollers and Ehmcke also employed Dixon's method for gases and the gasification products of fuel oils and determined the ignition point of benzene vapor. Dixon's ignition-point tester (Fig. 4) has a porcelain tube *a* of 55 mm (2.17 in.) inside diameter, which is converted into an electric heater by means of a surrounding coil of chrome-nickel wire and an insulating envelope. A glass tube *b* is cemented into the lower end of the porcelain tube. The nozzle consists of a tube *c* of difficultly fusible glass of 20 mm (0.79 in.) diameter with an opening of 1.7 mm (0.067 in.). The temperature is measured by means of a platinum-rhodium thermoelectric couple, which is introduced from below through the quartz tube *d* to a point just below the nozzle opening. It thus gives the temperature of the gas at the instant it comes in contact with the oxygen, the gas being introduced through *f* and the air or oxygen through *e*. The gas to be tested enters with a slow uniform flow, while the oxygen flows in like manner through the tube *a*, which is gradually heated. The explosion ensuing at the ignition temperature is indicated by a sharp report.

Lastly, Hawkes attempted to determine the ignition, so far as possible in accordance with the processes in the Diesel engine, by introducing fuel through a fuel valve into a heated cylinder filled with compressed air (Engineering, Vol. 110, 1920, p. 749).

He also measured the time from the beginning of the inflow to the instant of ignition ("ignition delay"). As shown by Fig. 5, the ignition temperature was found to depend, in a high degree, on the ignition delay. It is strange that thus far no one has determined the ignition temperatures directly in the Diesel engine, although possible with relatively simple means.

Wollers and Ehmcke determined the ignition temperature of benzene in drops by means of the ignition-point tester and in the form of vapor with the aid of the Dixon furnace, with practically like results. We might conclude from this that the fineness of the fuel particles does not matter. According to experiments with the Diesel engine, however, such is not the case, since the ignition delay was not taken into account. According to Hawkes' experiments, the ignition temperatures in oxygen are apparently the lowest obtainable, even with vaporized fuel oils, which are independent of the size of the drops. On the other hand, the time interval before ignition (i.e., the "ignition delay") is shortened in proportion to how finely the fuel is divided. In the Diesel engine, therefore, the ignition delay is just as important as the ignition temperature.

Hawkes found 260°C (500°F) to be the lowest ignition temperature for gas oil, the ignition delay being 3.5 seconds. The Essen laboratory obtained 255°C (491°F) with the ignition-point tester. For the ignition temperature of 380°C (716°F) the ignition delay in Hawkes' experiments with direct fuel injection was only $1/25$ second, while for the same ignition delay with fuel injection by means of

compressed air the ignition temperature was 40°C (72°F) higher. According to Hawkes, this temperature is much higher than the final temperature of the compressed air in the tested engine with a compression ratio of 11 : 1. Notwithstanding this, the engine started immediately from the cold condition, at this compression ratio, with gas oil.

This observation agrees also with our own. The starting of the cold engine with gas oil indicated that ignition occurred at about 350°C (662°F). The conditions in the engine differed, therefore, from those in the ignition-point tester of Hawkes. Due to the ignition delay, which may be estimated at 1/50 to 1/30 second in starting the engine, the ignition temperature for gas oil was about 100°C (180°F) higher than in the ignition-point tester. In other words, the temperature must be about 100°C higher than in the ignition-point tester, in order to enable the ignition to take place in the short time available. The same question is very easily answered for other fuel oils by assuming that the reaction speed or ignition delay is always the same for all fuel oils under like ignition conditions, whether in the ignition-point tester or in the engine. We may, therefore, assume that the ratio of the absolute ignition temperature in the engine to that in the ignition-point tester is constant for the different fuel oils.* From the values for gas oil, if T_z is the absolute temperature in the engine and

* As to how far the assumptions hold good, may perhaps be deduced from the teachings of theoretical chemistry. See Nernst, "Theoretische Chemie," editions 8-10, Stuttgart, 1921.

T_{zo} , that in the ignition tester, we accordingly obtain the desired value of this ratio:

$$\alpha = \frac{T_z}{T_{zo}} = \frac{350 + 273}{255 + 273} = 1.18$$

With the aid of this ratio, we can calculate the ignition temperatures in the engine from those in the ignition-point tester according to

$$T_z = \alpha T_{zo} = 1.18 T_{zo}$$

Table III gives the ignition points obtained in the Essen laboratory for the different fuel oils and, for the sake of comparison, the ignition points of the hydrocarbons related to the given fuel oils and also the temperatures T_z calculated from the ignition points.

Ignition points in the ignition-point tester and in the engine.

Fuel oil	In oxygen stream in V ₂ A steel crucible		In engine		Hydro-carbon	In oxygen stream in V ₂ A steel crucible		In engine	
	^C	^F	^C	^F		^C	^F	^C	^F
Gasoline	255°	491°	385°	725°	Hexane	283°	541°	383°	721°
Petroleum	232	450	323	613	Paraffin	246	475	340	644
	270	518	369	696	"	"			
	to		to		"	"			
	*279	534	378	712	"	"			
Gas oil	275	527	350	662	"	"			
Mexican fuel oil**	276	529	375	707	"	"			
Paraffin oil	240	464	332	630	"	"			
Light oil from natural tar	326	619	434	813	Phenol	590	1094	744	1371
Naphthalene oil	475	887	610	1130	Naphthalene	557	1035	705	1301
Anthracene oil	425	797	550	1022	Anthracene	493	919	630	1166
Haltermann tar oil	471	880	605	1121	Naphthalene & Anthracene				
Vertical furnace tar	465	869	597	1107	Benzene	570	1058	722	1332
					toluene	563	1045	713	1315
					xylene	530	986	674	1245
					cymene	445	833	574	1065

* According to Moore, The Essen value seems to be wrong.

** Determined in Kiel.

The ignition temperatures calculated for the engine can be regarded as only approximate. Their accuracy, individually, still requires verification.

In Fig. 6 the final temperatures T of the compression are plotted against the final pressures p , according to the formula of the adiabatic change of condition

$$T = T_0 \left(\frac{p}{p_0} \right)^{\frac{m-1}{m}}$$

for different initial conditions p_0 and T_0 (at the beginning of the compression). For the sake of simplicity, the same pressure was always chosen as the initial pressure, which usually exists at the end of the suction stroke of a four-stroke engine, namely $p_0 = 0.95$ atm. The exponent m of the compression was taken at 1.35. Denoting the initial temperatures by $T_0 = t_0 + 273$, the following values of t_0 correspond to the different conditions mentioned.

- $t_0 = 10^\circ\text{C}$ (50°F) for starting in the cold condition,
- $t_0 = 25^\circ\text{C}$ (77°F) for lowest speed with cold cooling-water,
- $t_0 = 50^\circ\text{C}$ (122°F) for full load with cold cooling-water or
for lowest speed with warm cooling-water at
 75°C (167°F),
- $t_0 = 75^\circ\text{C}$ (167°F) for full load with cooling-water at 75°C ,
- $t_0 = 100^\circ\text{C}$ (212°F) for full load with corresponding preliminary heating of the air introduced.

Reference must first be made to the still insufficiently known influence of the initial temperature on the final temperature T .

The effect of the pressure is considerably smaller. Thus an increase of 20°C (36°F) has the same effect as increasing the final pressure from 30 to 40 atmospheres. Temperature changes are therefore much more effective than pressure changes. Fig. 6 also contains, for comparison, the calculated ignition temperatures of the fuel oils and of benzene according to Table III.

We can now draw the following conclusions:

1. It is possible to start a cold engine only with gas oil and paraffin oil, gasoline and petroleum, Mexican fuel oil when sufficiently heated in advance, but not with tar oil.

2. Ordinary engines, with very hot cooling-water and high compression, can run under full load with all kinds of tar oils.

3. In order to render the Diesel engine capable of functioning under all loads with tar oil, some special means is required for raising the temperature in the combustion chamber and thereby accelerating the ignition, e.g., local heating of the combustion air, uncooled portions of the wall, or preliminary heating of the combustion air. Moreover, especially fine atomization accelerates the heating of the fuel oil, shortens the ignition delay and thereby lowers the ignition temperature.

4. Benzene is the most refractory fuel for the Diesel engine. The engine can be run with benzene only by employing, in strengthened form, the means mentioned above (in conclusion 3).

Combustion.— In the combustion following the ignition, the first

drops of fuel injected into the combustion chamber cause a local heating of air. At these points, the temperature rises to 2000°C (3632°F) and higher. The succeeding fuel therefore finds very different conditions than existed before the first ignition. There are now two possibilities:

1. The fuel comes in contact with pure air, ignites immediately and burns;

2. The fuel first comes in contact with the flame, consequently in a region poor in oxygen, finds the conditions for pyrogenetic decomposition and, after this decomposition, first encounters the oxygen of the combustion air.

Of course, these two conditions constitute the limits between which lie all the possible gradations. It is therefore necessary to distinguish between the combustion of the undecomposed and of the decomposed oil particles.

The chemical process of the combustion of the undecomposed oil includes a large number of intermediate steps, the significance of which, for the combustion process in the Diesel engine, must yet be investigated. In this connection, especial efforts should be made to determine whether and how the combustion process differs for aliphatic and aromatic fuels. Von Wartenberg seems to hold the opinion that aromatic fuels, in contrast with the aliphatic, have a tendency to deposit soot during combustion, on account of their greater carbon content.

The chemical process of combustion of the pyrogenetically decom-

posed fuels differs greatly for aliphatic and aromatic fuels.

Fischer says: "The aromatic hydrocarbons of coke tar behave quite differently from the presentation in Riedler and Löffler's book. Xylene, for example, on being heated, passes through the following stages: at first, the molecule is made smaller by the breaking off of the side chains, whereby, at temperatures between 600 and 800°C (1112 and 1472°F), with the temporary formation of toluene, benzene is formed at the expense of the methyl and ethyl and other side chains. From this point on, however, the molecule grows larger instead of smaller, diphenyl compounds being formed with the liberation of hydrogen. The molecules grow larger with the continuous loss of hydrogen, until only a large carbon skeleton remains. Since with an insufficient supply of air or too rapid cooling of the flames, the hydrogen and the other more combustible small molecules of gas burn first, the combustion tends to end with the formation of much soot, in contrast with the previously described combustion of aliphatic hydrocarbons, in the disintegration of which only rapidly burning small gas molecules are formed. The phenols and their homologs, which occur in greater or less quantities in tars and tar oils, burn in a similar manner, with the evolution of soot." *

These considerations compel us to conclude that pyrogenetic decomposition should be prevented (especially in aromatic fuels), since it results in the formation of soot. The means for remedying

* "Die neuesten Anschauungen über die Vorgänge bei der Verbrennung und der Oxydation der Kohlen," Abhandlung (treatise) IV, p.452.

this difficulty are the same as for ignition, namely, the quickest possible ignition at the highest possible temperature. This can best be accomplished by means of the injection air, which first absorbs the fuel in the form of very small drops and then, as the result of the great velocity with which it leaves the nozzle, quickly and uniformly distributes it throughout the whole combustion chamber. The fuel and air must be mixed in definite proportions and there must be a definite distribution as regards both time and space, so that the local fuel temperatures will correspond with the oxygen content.

The only economical means now known for distributing the fuel particles more rapidly in the combustion chamber, is the generation of a whirling motion in the combustion air. I have myself previously gone thoroughly into this matter (*Jahrbuch der Schiffbautechnischen Gesellschaft*, Vol. 21, 1920, p.318). This method can be employed, either by generating the whirling motion by means of the inflowing combustion air, in either the two-stroke or four-stroke cycle, or by injecting special air of lower or higher tension (according to the instant of its injection) into the combustion chamber. Both methods have indeed long since been proposed, but have never been tried out in practice with sufficient thoroughness.

Recently, however, Neumann has gone thoroughly into the question of the after-burning, which is closely connected with the course of the combustion itself and with the degree of whirling during the combustion ("*Untersuchungen an der Dieselmachine*," *Forschungsarbeiten*, No. 245). Thus far, no one has thoroughly investigated the

relation between the reaction speed and the after-burning. It is certain that the different fuel oils and their decomposition products burn at very different speeds and that the aromatic fuels, probably on account of the liberation of carbon, burn slower than the aliphatic fuels.

It is the business of the constructors to utilize the results of the scientific study of fuels and their combustion by the suitable adaptation of the engines. I can demonstrate by three examples that the ignition temperatures given above approximately agree with the reality. Figs. 7 to 12 show both full load and idling speed indicator diagrams for anthracene oil, naphthalene oil and benzene. The comparative experiments were performed with a vertical, single-cylinder, four-stroke-cycle engine of 300 mm (11.81 in.) cylinder diameter and 450 mm (17.72 in.) stroke at about 200 R.P.M., which was provided with the devices of the Friedrich Krupp Company for the combustion of tar oil alone. While running at the minimum speed, no misfires occurred with anthracene oil, but they did occur with naphthalene oil whose ignition temperature, according to Table III, is about 60°C (108°F) higher (Figs. 8 and 10). In order to make this difference clear, the compression in the engine was purposely made low (about 30 atm. final pressure). At a somewhat higher compression (and correspondingly higher final temperature) the misfires ceased to occur with naphthalene oil.

The higher ignition temperature of benzene necessitated a considerable increase in the final compression temperature. For this

purpose the final compression pressure was raised to 45 atm. and the temperature of the combustion air to about 60°C (140°F). It was then possible, as shown by Figs. 11 and 12, to run the engine under any load. The preliminary heating and compression corresponded to a final temperature of about 730°C (1346°F), while Table III gives 722°C (1332°F) as the ignition temperature for benzene in the engine.

In closing this paper, I wish to call attention to the services of Holm. With the encouragement of Kutzbach, he first determined the ignition temperatures of liquid and solid fuels and recognized their technical importance and their relation to the chemical constitution of the fuels.

Translation by Dwight M. Miner,
National Advisory Committee
for Aeronautics.

- 1 Napthalene oil
- 2 Haltermann tar oil.
- 3 Lindenhof tar oil
- 4 Anthracene oil

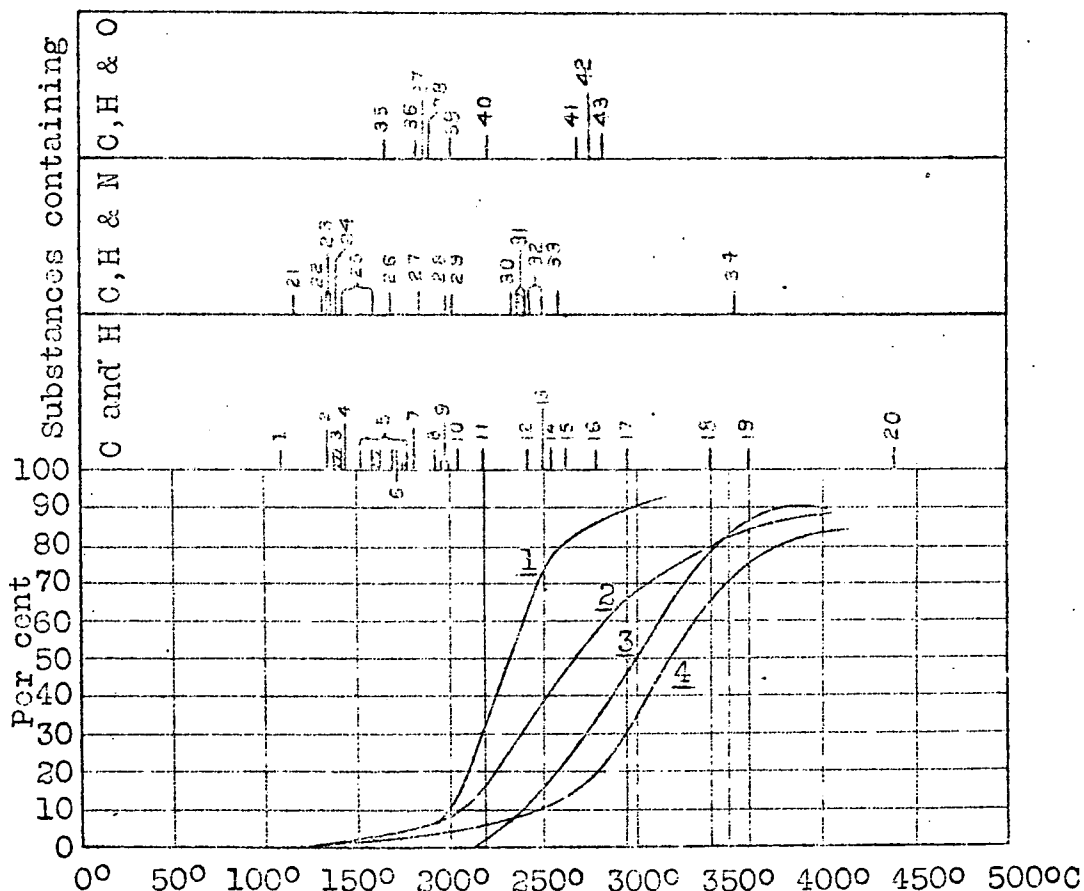


Fig.1. Boiling curves of tar oils and boiling points of tar-oil hydrocarbons.

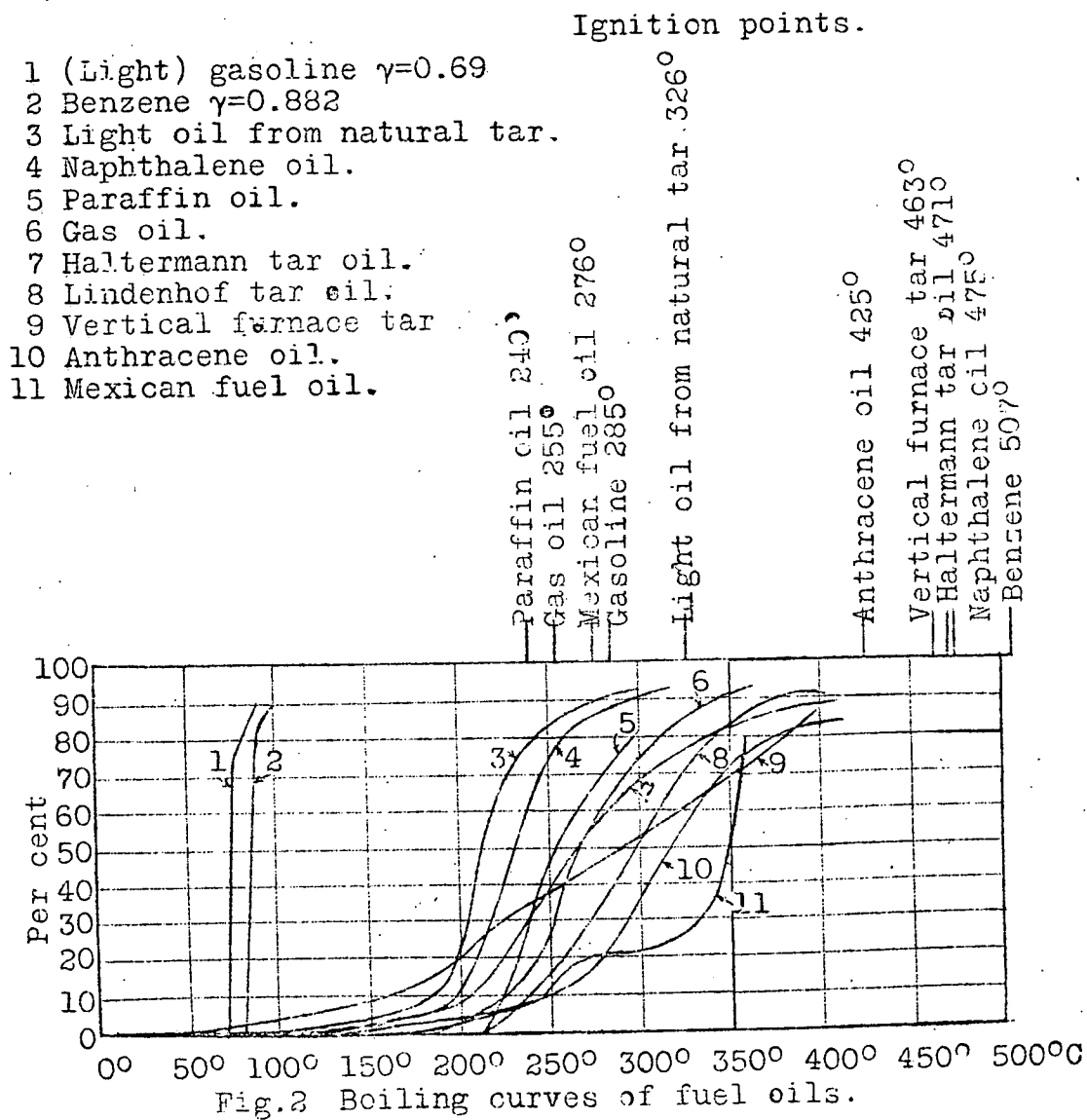
Key on following page.

K e y

- 1 = C_7H_8 toluene
- 2 = C_8H_{10} ethylbenzene
- 3 = C_8H_{10} xylene p, m, o
- 4 = C_8H_8 styrene
- 5 = C_9H_{12} { isopropylbenzene
ethyltoluene p, m, o
pseudocumene
hemellitene
- 6 = $C_{10}H_{12}$ decane
- 7 = C_9H_8 indene (C_9H_{10} hydroindene)
- 8 = $C_{10}H_{14}$ durene
- 9 = $C_{10}H_{10}$ methylinde~~ne~~
- 10 = $C_{10}H_{12}$ tetrahydronaphthalene
- 11 = $C_{10}H_8$ naphthalene
- 12 = $C_{11}H_{10}$ methylnaphthalene
- 13 = $C_{16}H_{38}$ paraffin
- 14 = $C_{12}H_{10}$ diphenyl
- 15 = $C_{12}H_{12}$ dimethylnaphthalene
- 16 = $C_{12}H_{10}$ acenaphthene
- 17 = $C_{13}H_{10}$ fluorene
- 18 = $C_{14}H_{10}$ phenanthrene
- 19 = $C_{14}H_{10}$ anthracene
- Above 360° = { $C_{15}H_{12}$ methylantracene
 $C_{15}H_{10}$ fluoranthene
 $C_{16}H_{10}$ pyrene
- 20 = $C_{18}H_{12}$ chrysene

21 =	C_5H_5N	pyridin
22 =	C_4H_5N	pyrol
23 =	C_6H_7N	picolin α, β
24 =	C_6H_8N	thioxene
25 =	C_7H_9N	lutidin $\alpha \alpha$ $\alpha \gamma$
26 =	C_8H_7N	trimethylpyridin
27 =	C_6H_7N	anilin
28 =	C_7H_5N	benzonitril
29 =	C_7H_9K	toluidin
30 =	$C_9H_{23}N$	tetramethylpyridin
31 =	C_9H_7N	quinolin
32 =	C_8H_7N	indol
33 =	$C_{10}H_9N$	methylquinolin
34 =	$C_{12}H_9N$	carbazol
Above 360° =	$\begin{cases} C_{13}H_{11}N \\ C_{13}H_9N \end{cases}$	hydroacridin acridin
Above 440° =	$C_6H_{11}N$	phenylnaphthylcarbazol

35 =	C_8H_6O	coumarone	
36 =	C_6H_6O	phenol	
37 =	C_7H_8O	cresol, o	o = ortho m = meta p = para
38 =	C_9H_8O	methylcoumarone	
39 =	$\begin{cases} C_7H_8O \\ C_8H_8O \end{cases}$	cresol p, m acetophenone	
40 =	$C_8H_{10}O$	xlenol	
41 =	$C_{10}H_8O$	naphthol α	
42 =	$C_{12}H_8O$	diphenyloxide	
43 =	$C_{10}H_8O$	naphthol β	



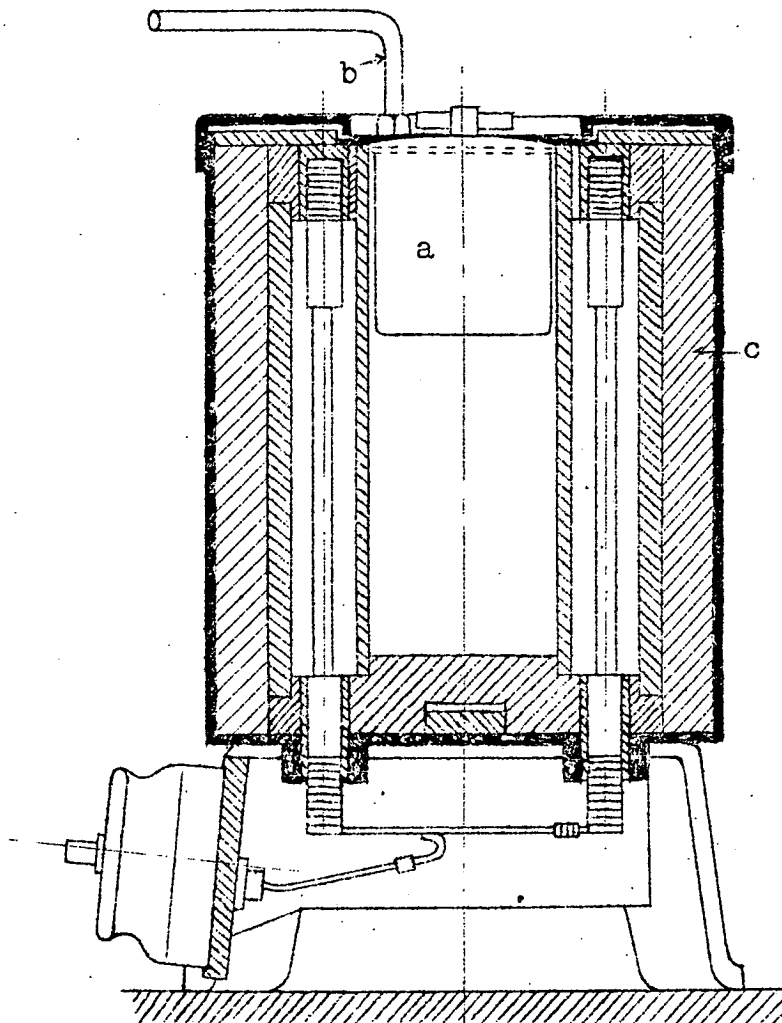


Fig. 3. Electric furnace with ignition block of Krupp ignition-point tester.

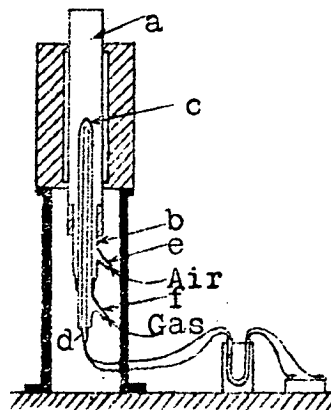


Fig. 4. Dixon ignition-point tester.

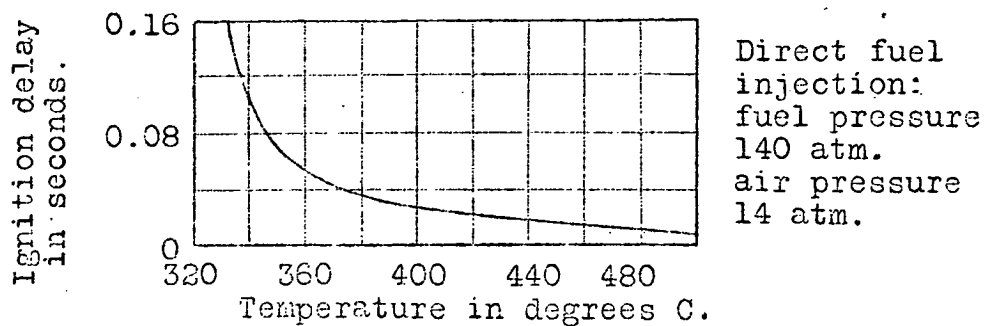


Fig.5. Ignition temperatures for gas oil, according to Hawkes.

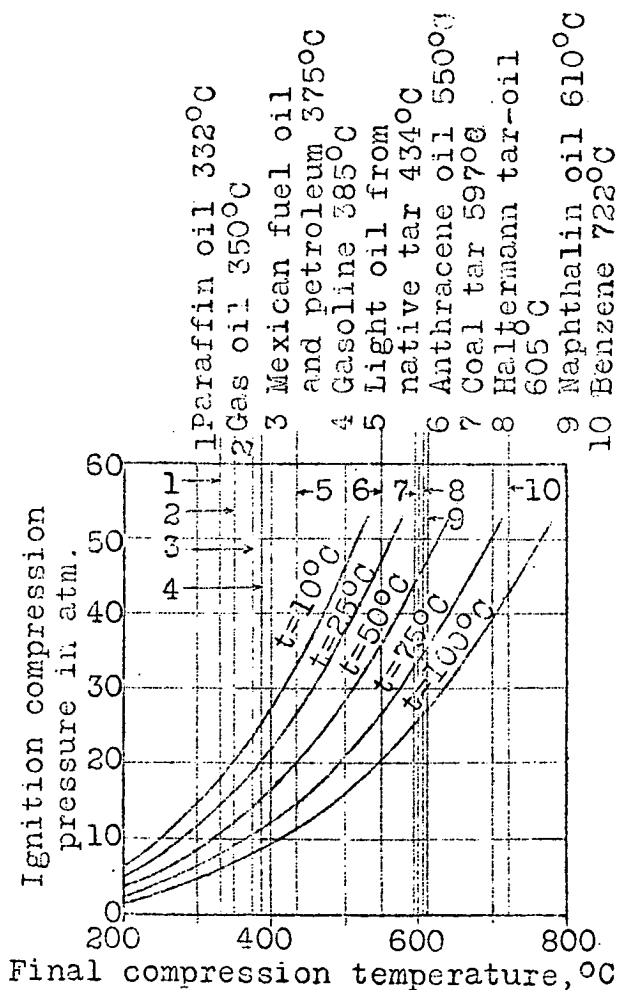


Fig.6. Compression pressure, final compression, temperature and ignition temperature in Diesel engine.

Indicator diagrams.



Fig.7.

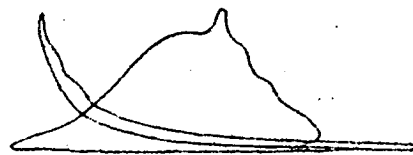


Fig.8.

With anthracene oil.



Fig.9.



Fig.10.

With naphthalene oil.

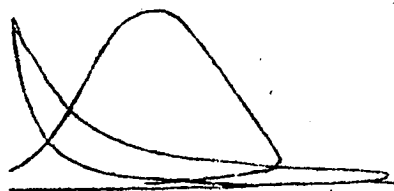


Fig.11.

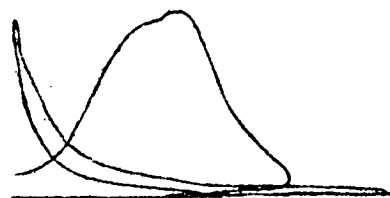


Fig.12.

With benzene.